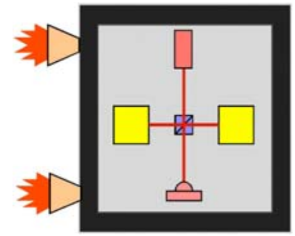


The ST7-DRS Mission: Status and Plans

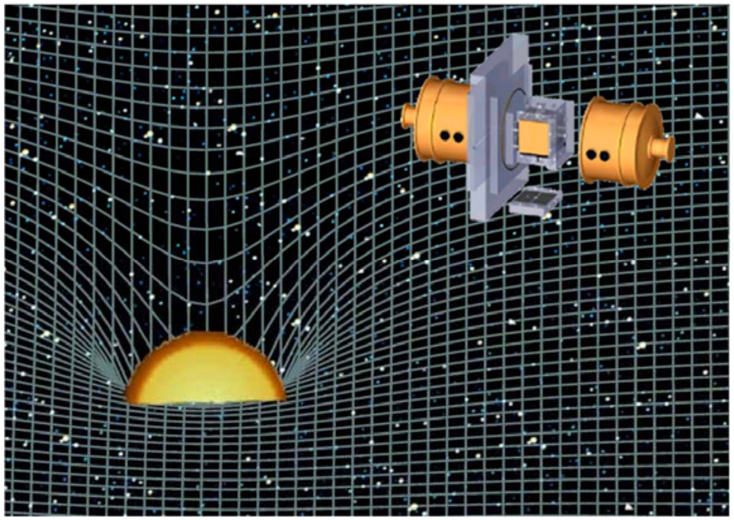
Charles Dunn, **William Folkner**, Phillip Barela

June 28, 2006

ST7 - Disturbance Reduction System (DRS)

Salient Features

- DRS flies on the ESA LISA Pathfinder spacecraft
- Sun-Earth L1 halo orbit
- Drag-free satellite to offset solar pressure
- Payload delivery: Aug 2007 (TBR)
- Launch date: Oct 2009
- Operational life: 3 months
- Data Analysis: 12 months



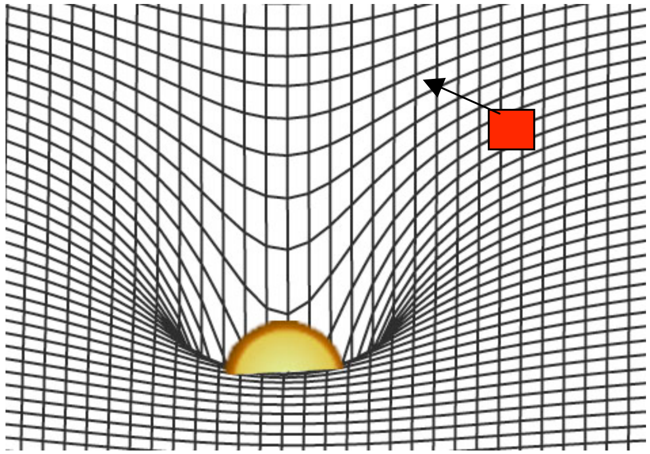
Technologies

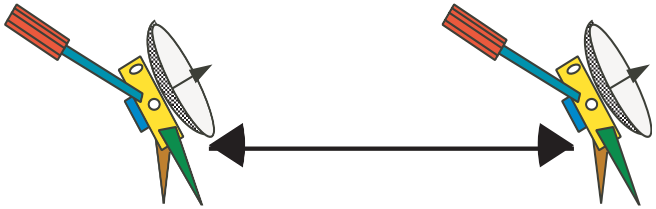
- The Disturbance Reduction System (DRS) will validate system-level technologies required for use on future gravity and formation flying missions.

- The key new technologies are microthrusters for nanometer-level spacecraft control
  - DRS will validate spacecraft position control to an accuracy of <10nm/sqrt(Hz) over frequency range 1 mHz to 30 mHz (Precision Flight Validation Experiment)
  - DRS will validate spacecraft control compatible with a test mass following trajectory determined by gravitational forces only within $3\mathrm{x}10^{-14}$ m/s^2/sqrt(Hz) over frequency range 1 mHz to 30 mHz

ST7-DRS Goals

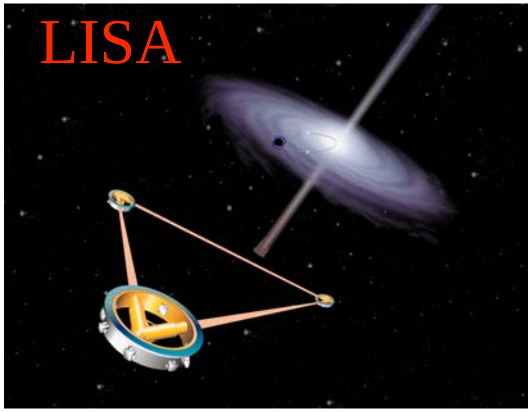
- DRS is designed to validate a system of technologies to reduced disturbance forces acting on a reference test mass
  - Low acceleration noise on test masses is required for study of general relativity, planetary gravity, gravitational waves
- To reduce disturbances from motion of spacecraft on test mass, ST7 will control the position of the spacecraft to < 10 nm
  - Ability to control spacecraft to fraction of wavelength of light could be used in separated-spacecraft interferometry missions

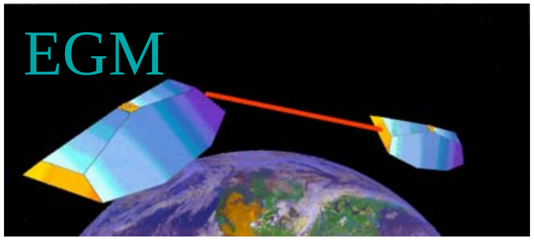




Future Gravity Missions

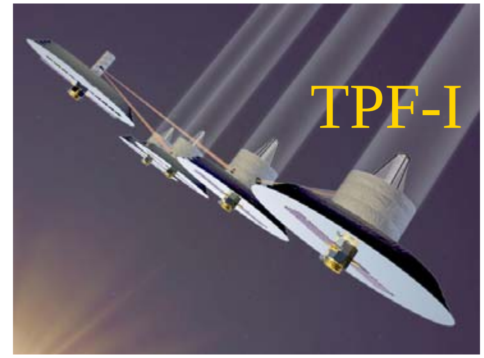
- LISA (Laser Interferometer Space Antenna)
  - Low-frequency gravitational waves
  - Acceleration noise < 3×10^{-15} $m/s^2/\mathrm{sqrt(Hz)}$
    - From 10^{-4} Hz to 10^{-2} Hz
- EGM (Earth Gravity Mapper)
  - Time-varying Earth gravity
  - Acceleration noise <1×10^{-11} $m/s^2/\mathrm{sqrt(Hz)}$
    - From 1 Hz to 10^{-3} Hz
- LIRE (Laser Interferometer Ranging Experiment)
  - Solar system test of general relativity
  - Acceleration noise < 3×10^{-15} $m/s^2/\mathrm{sqrt(Hz)}$
    - From 10^{-4} Hz to 10^{-2} Hz

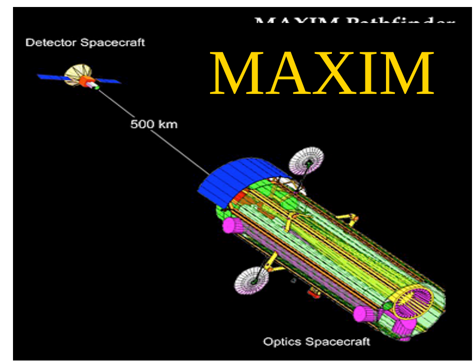


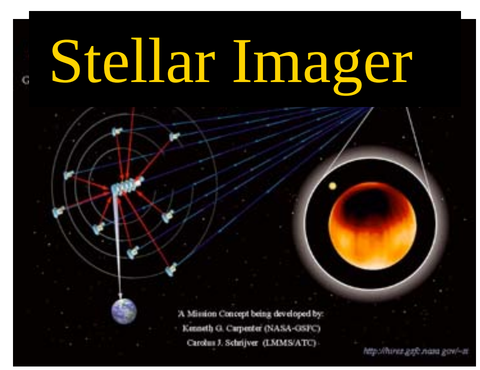


Future Interferometry Constellations

- TPF-I (Terrestrial Planet Finder Interferometer)
  - IR imaging of planetary systems
  - Position control goal < 30 μm rms
    - For some possible configurations
- MAXIM (MicroArcsecond X-ray Interferometer Mission)
  - X-ray imaging of black holes
  - Position control goal < 10 nm rms
- Stellar Imager
  - UV imaging of other stars
  - Position control goal < 10 nm rms

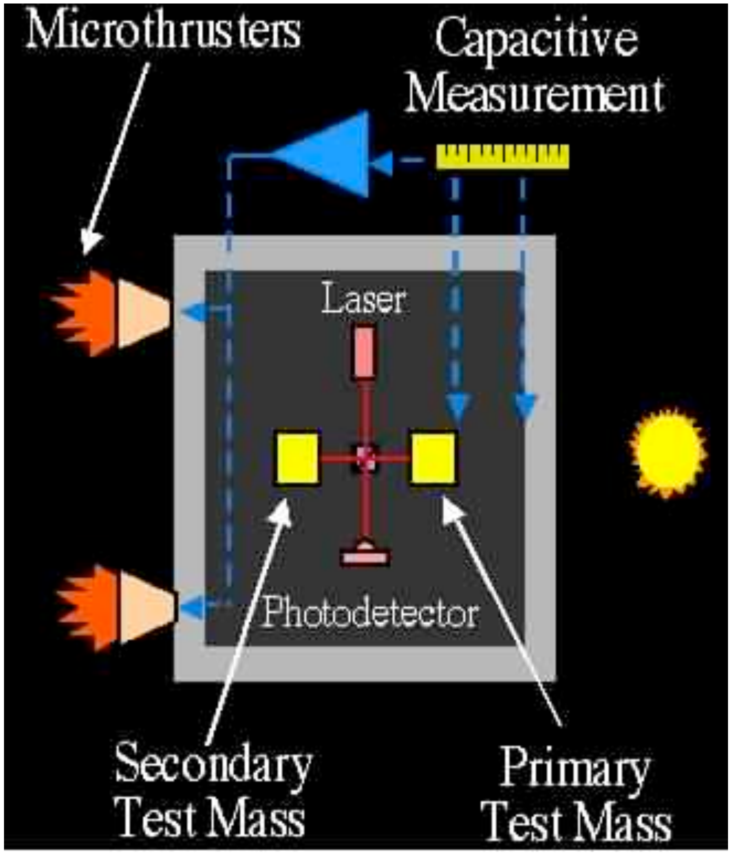






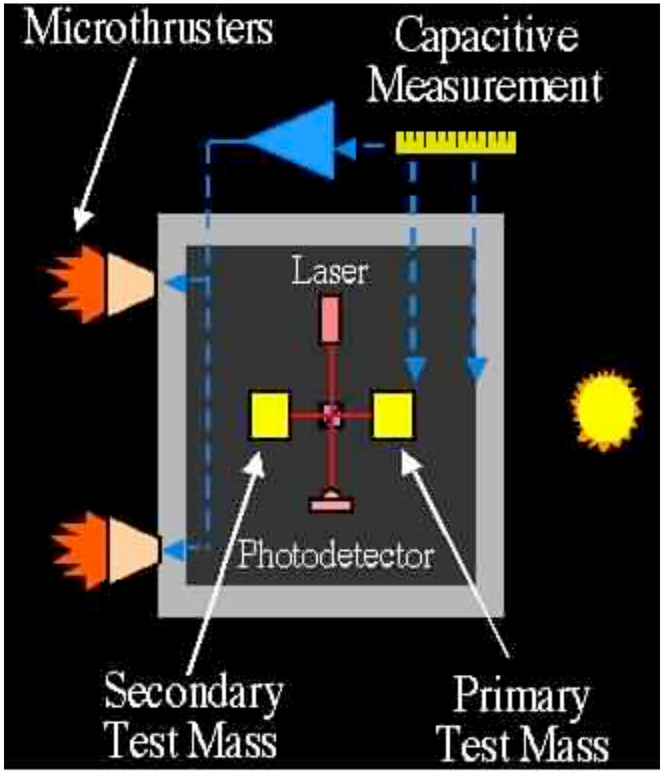
ST7 Concept

- Objective is to validate control system (thrusters/algorithms) with performance capable of meeting needs of future gravitational missions
  - To achieve acceleration noise requirement, spacecraft position must be controlled to 10 nm/sqrt(Hz)
  - Spacecraft control precision requires new class of thruster technology
- System performance is defined by position control with respect to freely-floating test mass and acceleration noise on test masses (inferred)
  - Acceleration noise performance is validated by comparing position of reference test mass to position of second test mass



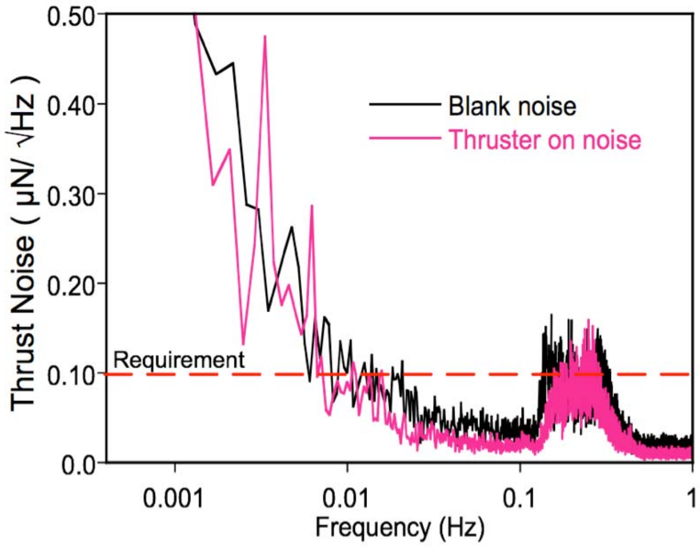
Top Level Requirements

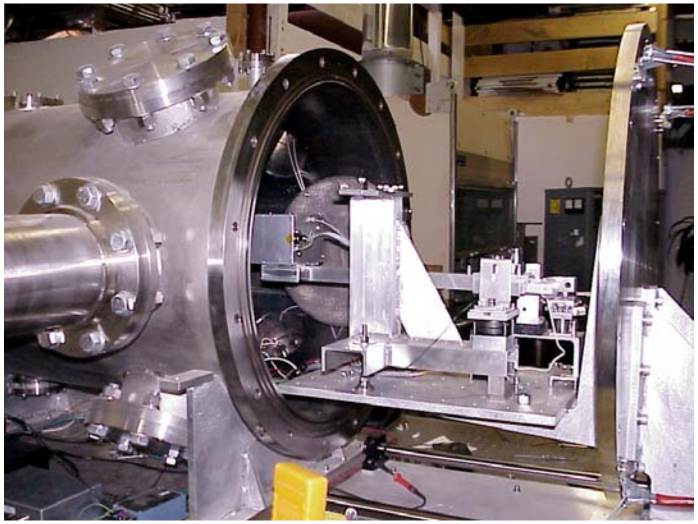
- Propulsion:
  - Two clusters of four thrusters
  - 5 μN to 30 μN capability per thruster
  - 0.1 μN resolution
  - Less than 0.1 μN/sqrt(Hz) noise
    - Over bandwidth 1-30 mHz
- Sensor (Provided by ESA)
  - Less than 5 nm/ sqrt(Hz) noise
    - Over bandwidth 1-30 mHz
    - Measurement rate 5 Hz
- Control System
  - Less than 10 nm/sqrt(Hz) position control
  - 10 Hz control update rate



Need for Flight Validation

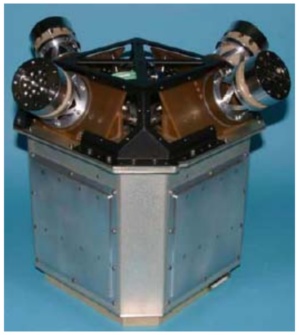
- Available thrust stands are unable to measure thrust noise at low frequencies (<10 mHz);
- Performance of inertial sensor requires a factor of 30,000 improvement from current state of the art, and can not be tested in a 1g environment;
- The mechanical noise contributions due to the environment and spacecraft bus equipment have never been measured at the required levels.





DRS Element Summary

Micro-Thrusters



>12,000 Hrs. on thruster Design

Life testing in progress

Flight fabrication mostly Complete
(except thruster heads)

Delivery 10/17/06

GSFC

Dynamic Control System

Control System Software delivered 6/7/06

Inertial Sensor Model Update 10/06

Broad Reach Engineering
Space Flight Hardware & Vehicle Design

Integrated Avionics

Tested & Delivered 5/2/06

Project Management

C&DH Software
-Acceptance test begin 2/3/06
-Delivery 8/17/06

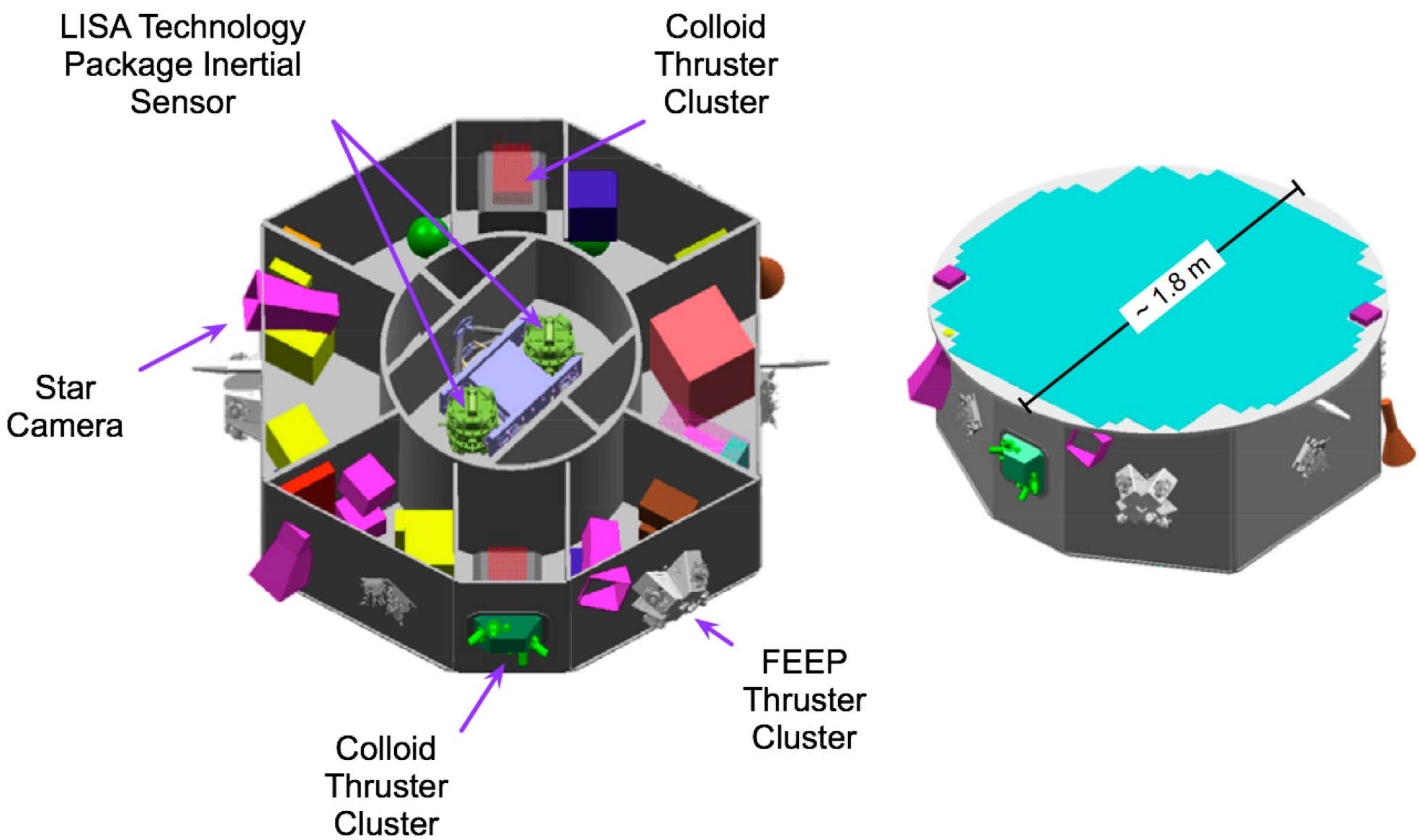
Structures
-CBH delivered 12/15/05
-Mass dummies & lifting sling complete

Cabling/Harness
-FM cables delivery 7/31/06

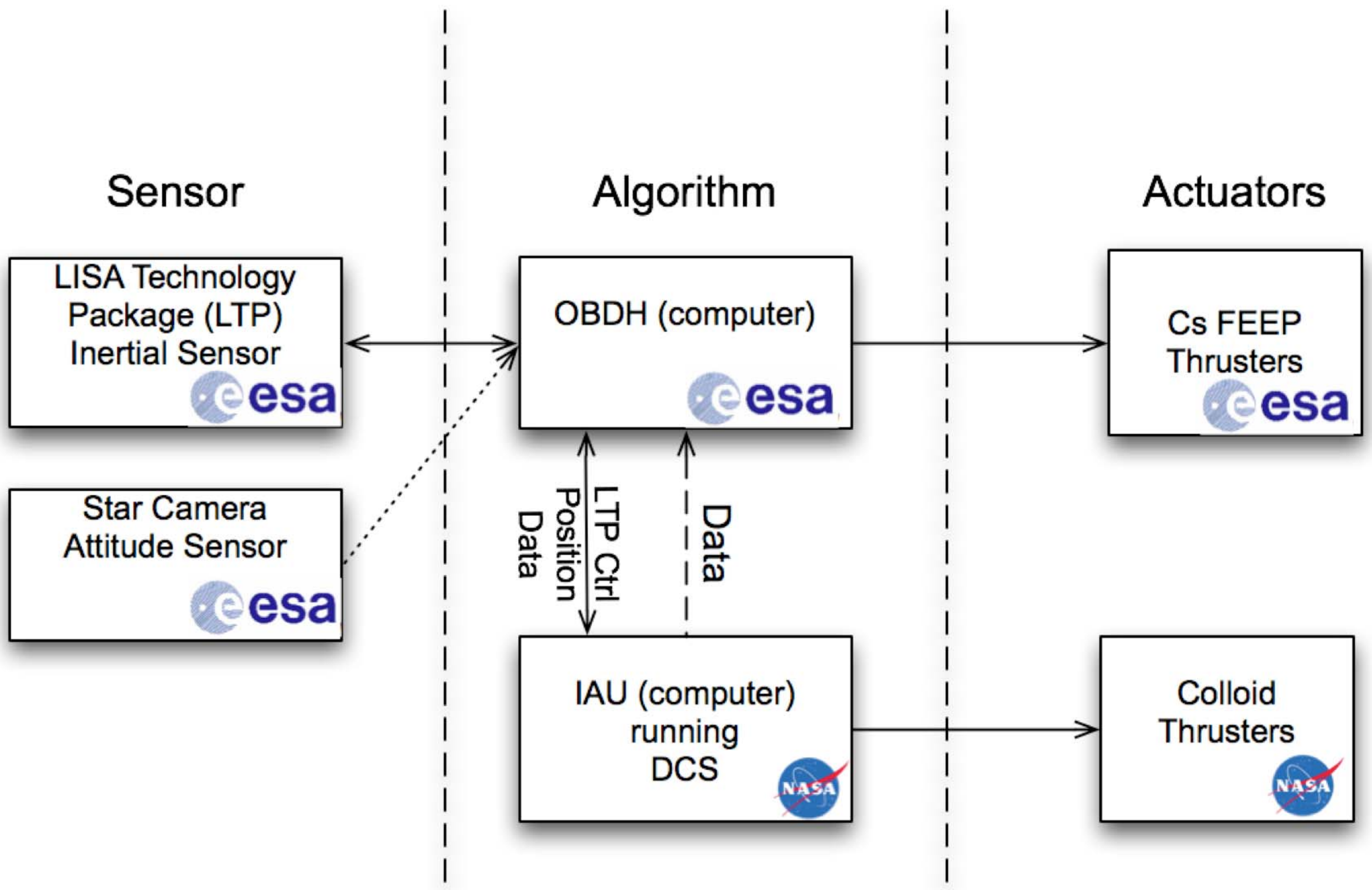
I&T
-Begins 9/1/06
-Facilities ready
-Funded schedule slack at 22 days
-Instrument Delivery 3/31/07

Operations
-D-CDR 4/19/2006

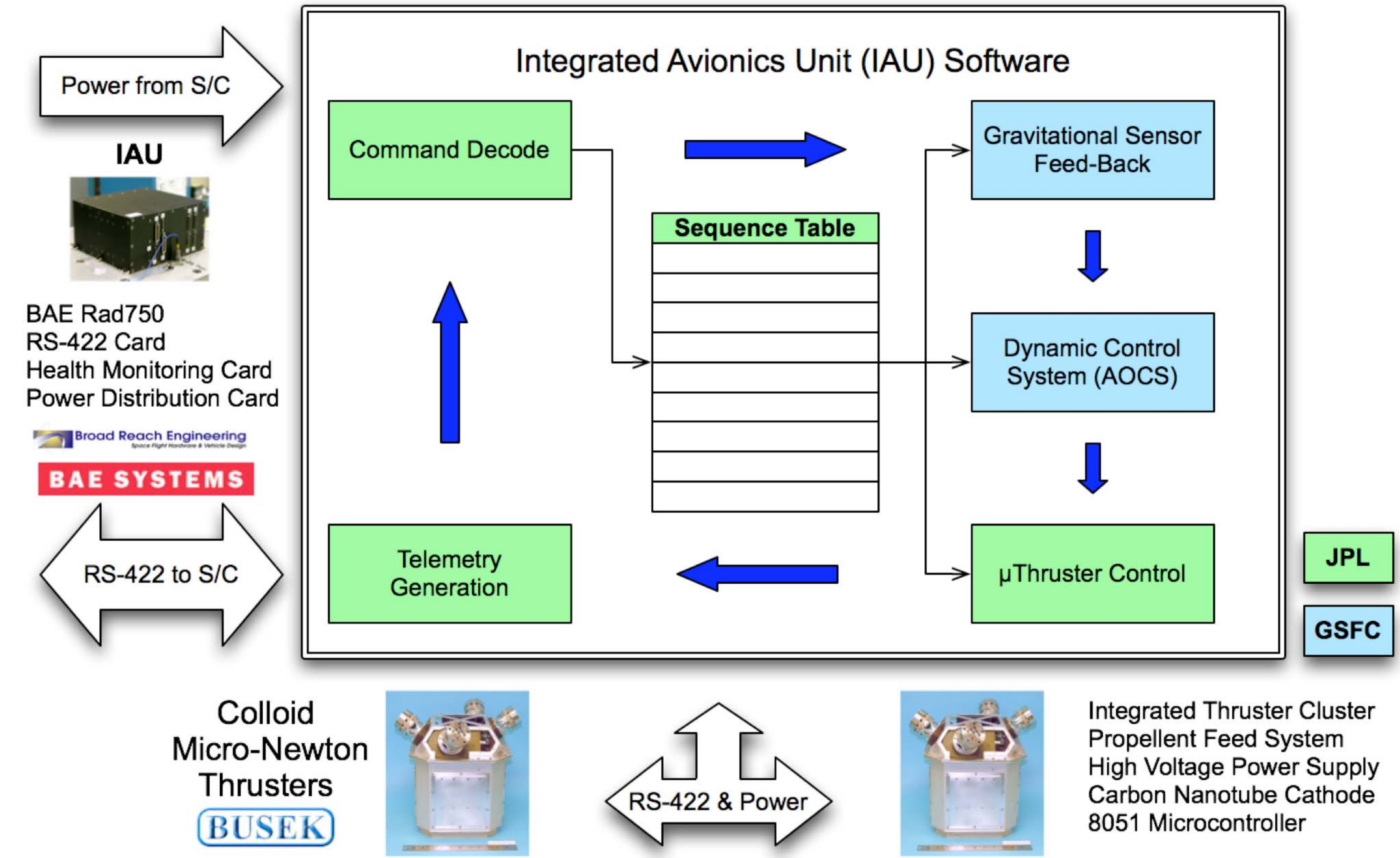
LISA Pathfinder Spacecraft



LISA Pathfinder Elements

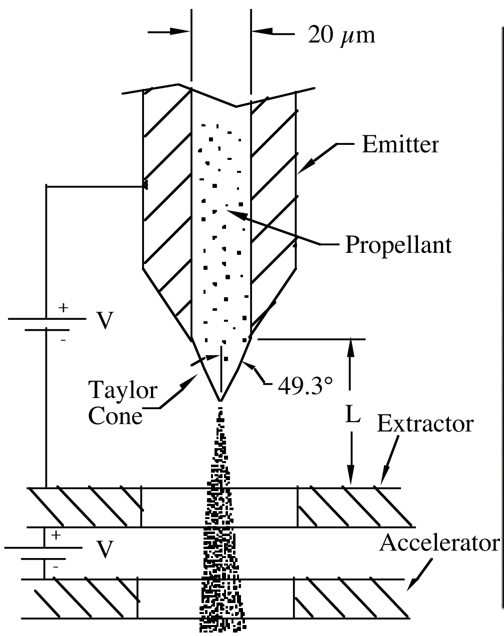


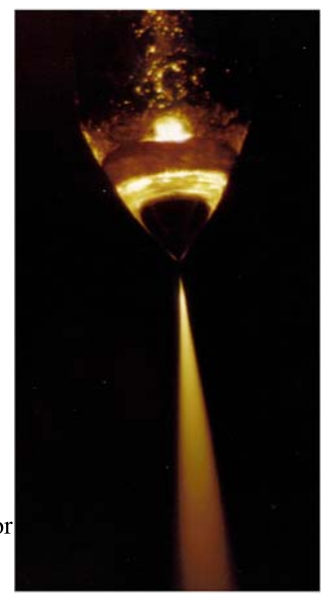
DRS Interfaces

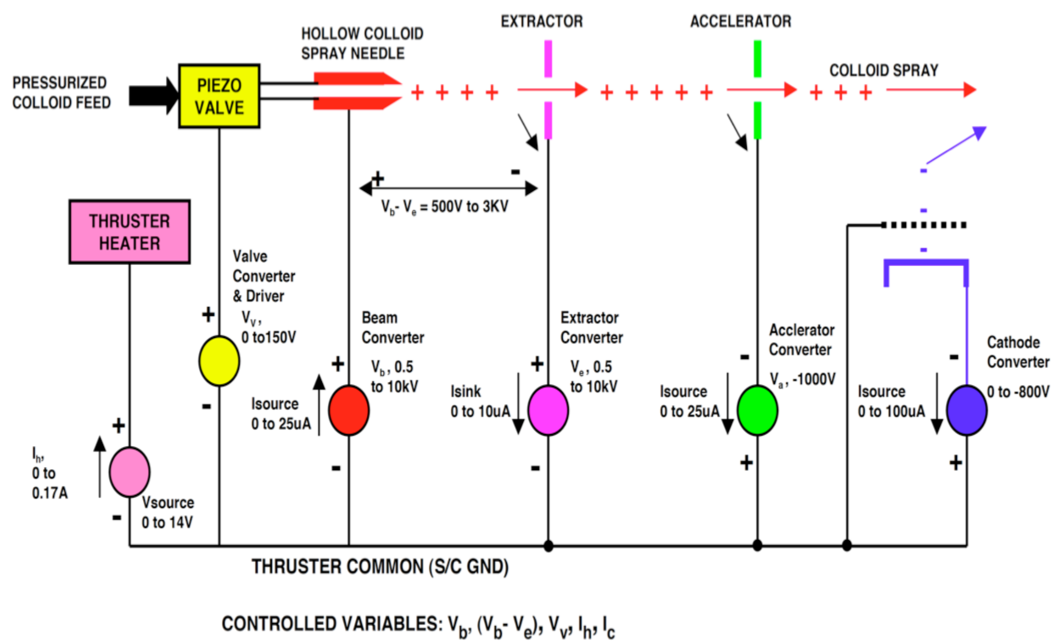


Colloid Microthrusters

- Propellant is conductive liquid with low vapor pressure;
- Charged droplets are ejected through action of high voltage;
- Thrust is controlled by fluid current and acceleration voltage;

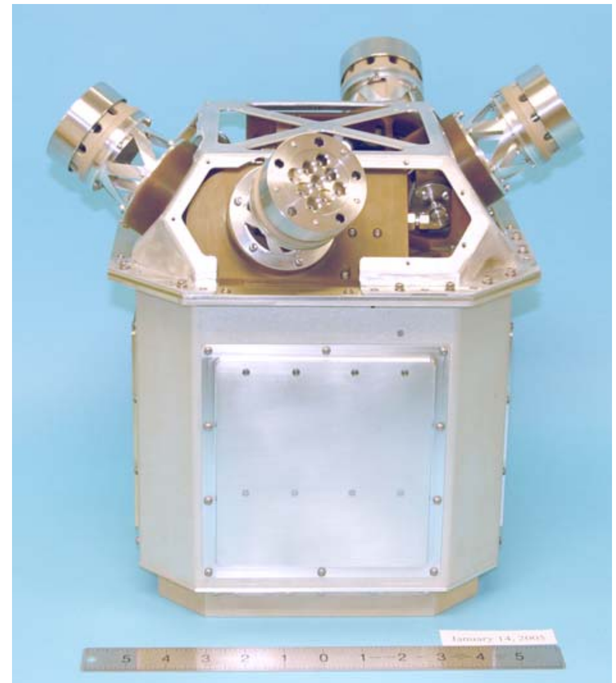




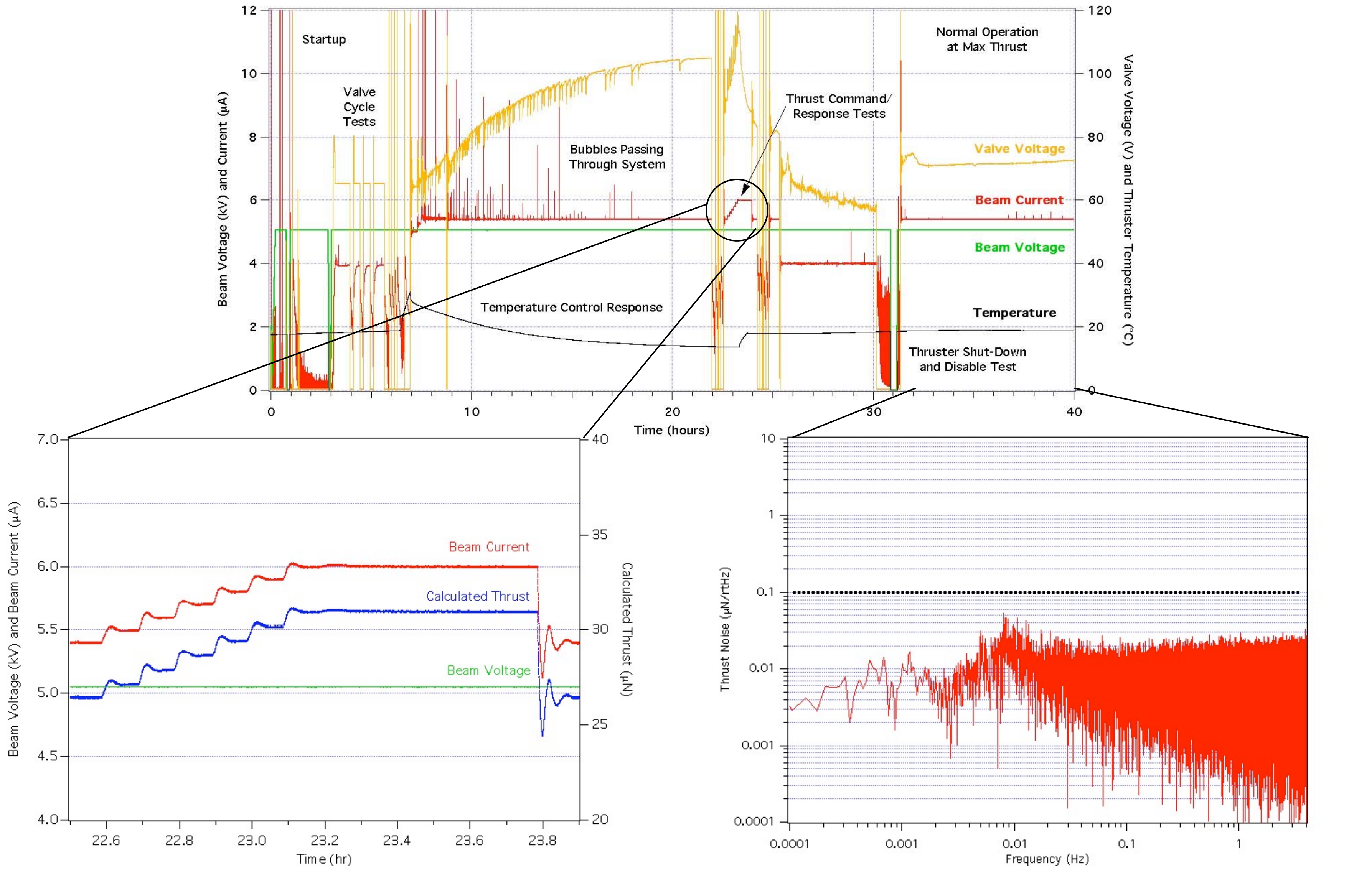


Microthruster Development

- Design has progressed to evaluation of
  - integrated, flight-like, assemblies including:
    - Spring loaded bellows
    - Microvalve
    - Nine-needle thruster head
    - High voltage electronics
- Bubbles in propellant are a major challenge
  - Primarily Water;
  - Results in ‘overspray’ potentially resulting in shorting;
  - Increases thrust level time constant;
- Addressed by cleanliness/handling procedures & design features to eliminate bubbles.



Microthruster Testing

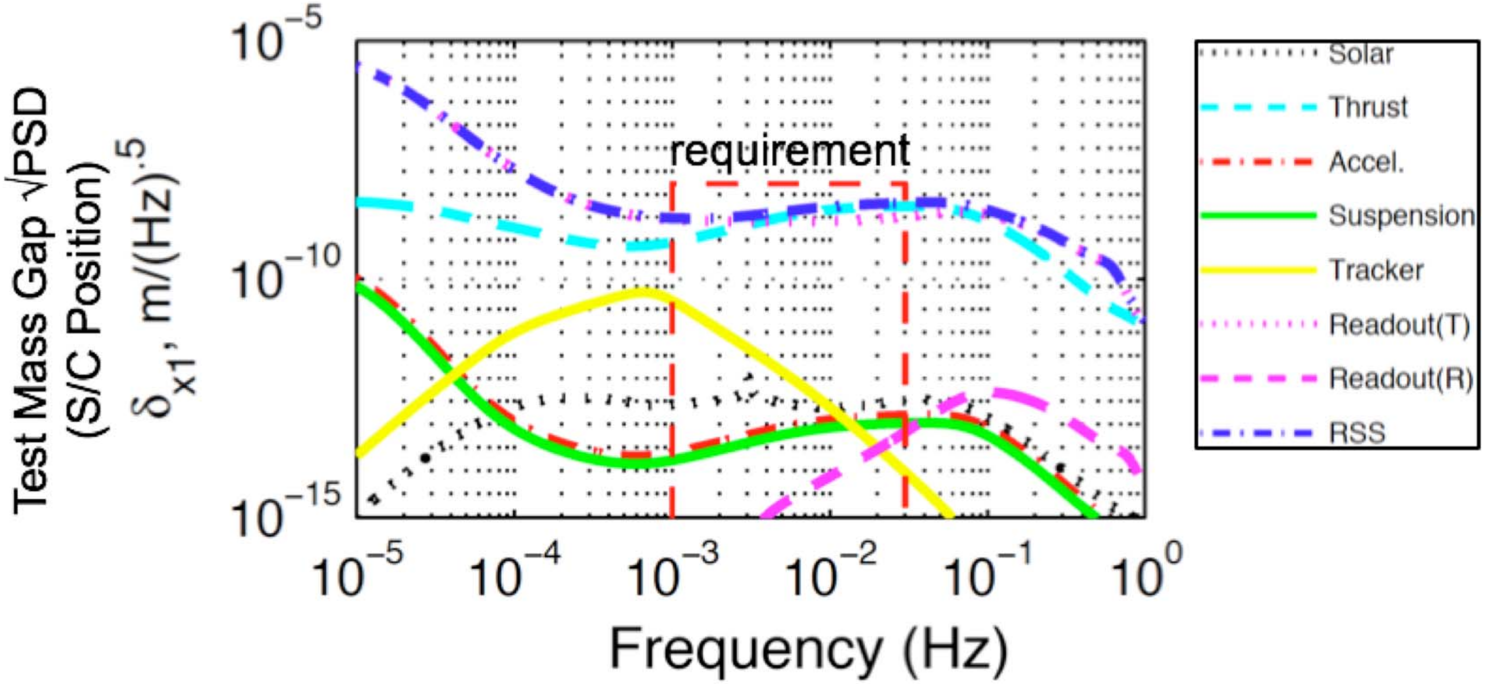


Microthruster Status

- Flight assembly has begun.
- Life testing in process.
- Final changes to thruster head design are still possible.

Dynamic Control Software Status

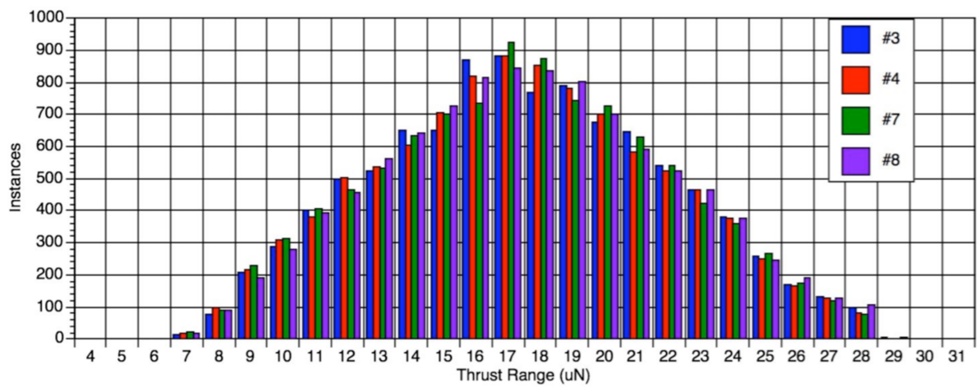
- Completed linear & non-linear performance simulations;



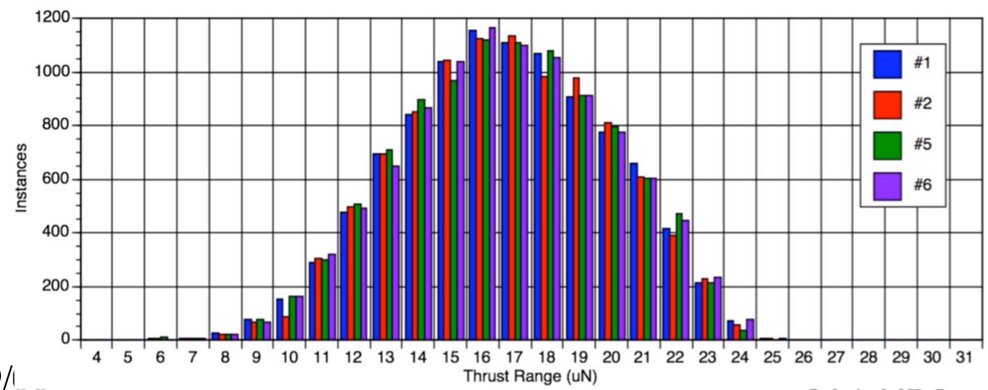
Dynamic Control Software Status

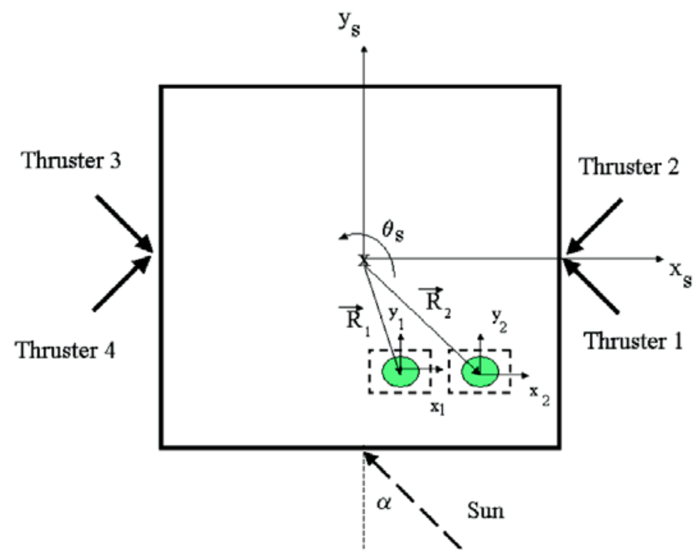
- Force and Torque authority addressed by monte-carlo analysis over requirement ranges:

Thrusters opposite to Solar Radiation Pressure



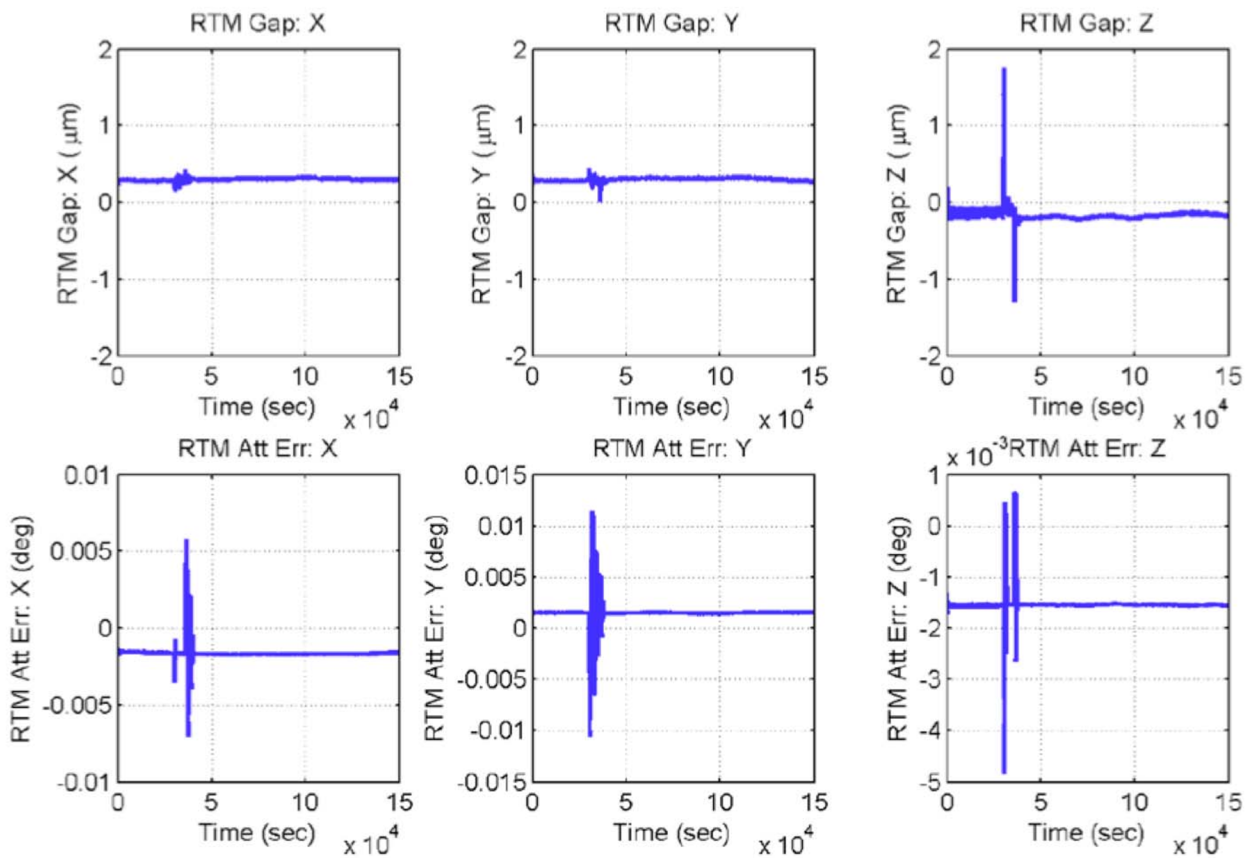
Thrusters adding to Solar Radiation Pressure





Dynamic Control Software Status

- Mode transition simulations:
  - *e.g.* transition to drag-free control

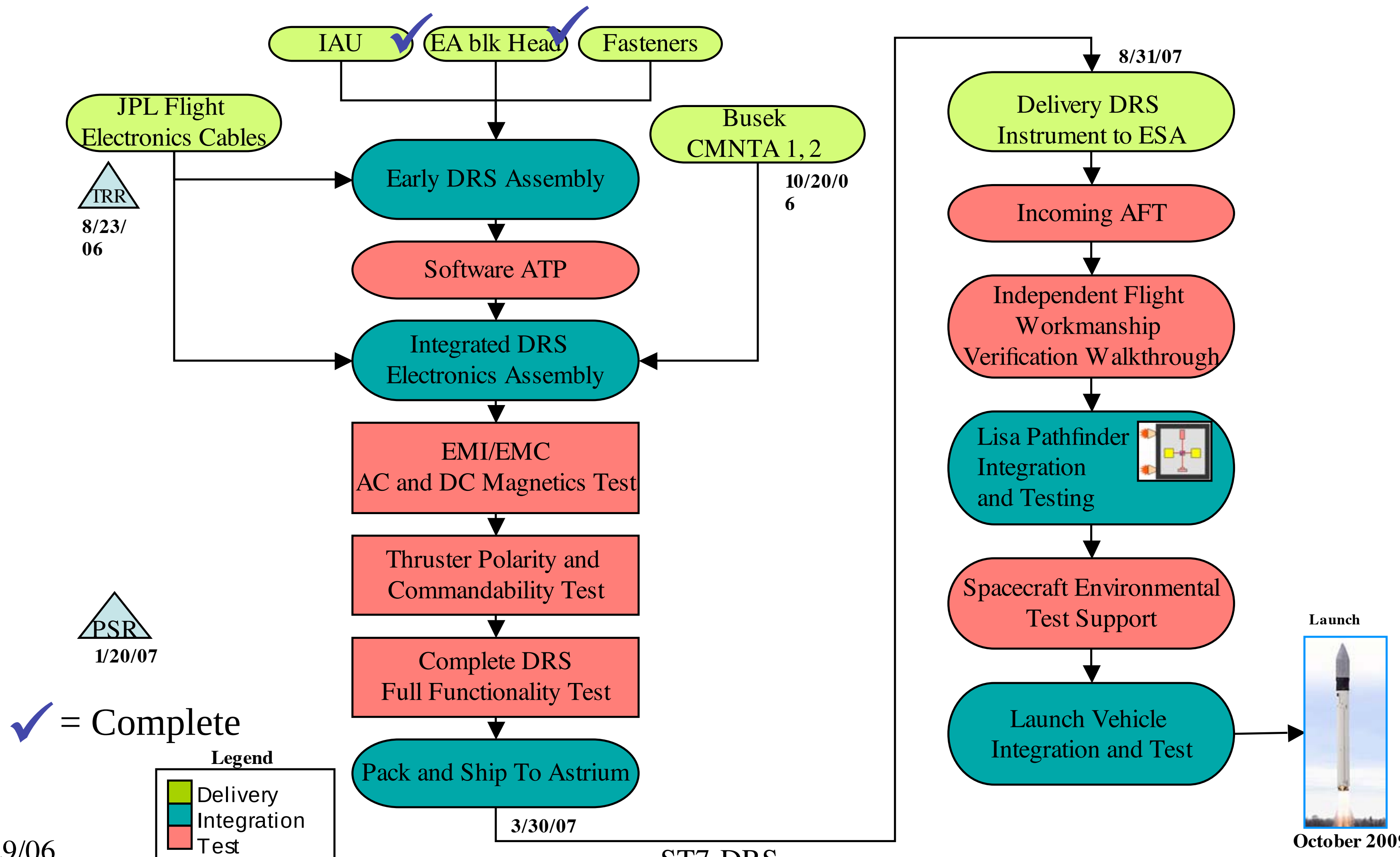


Summary

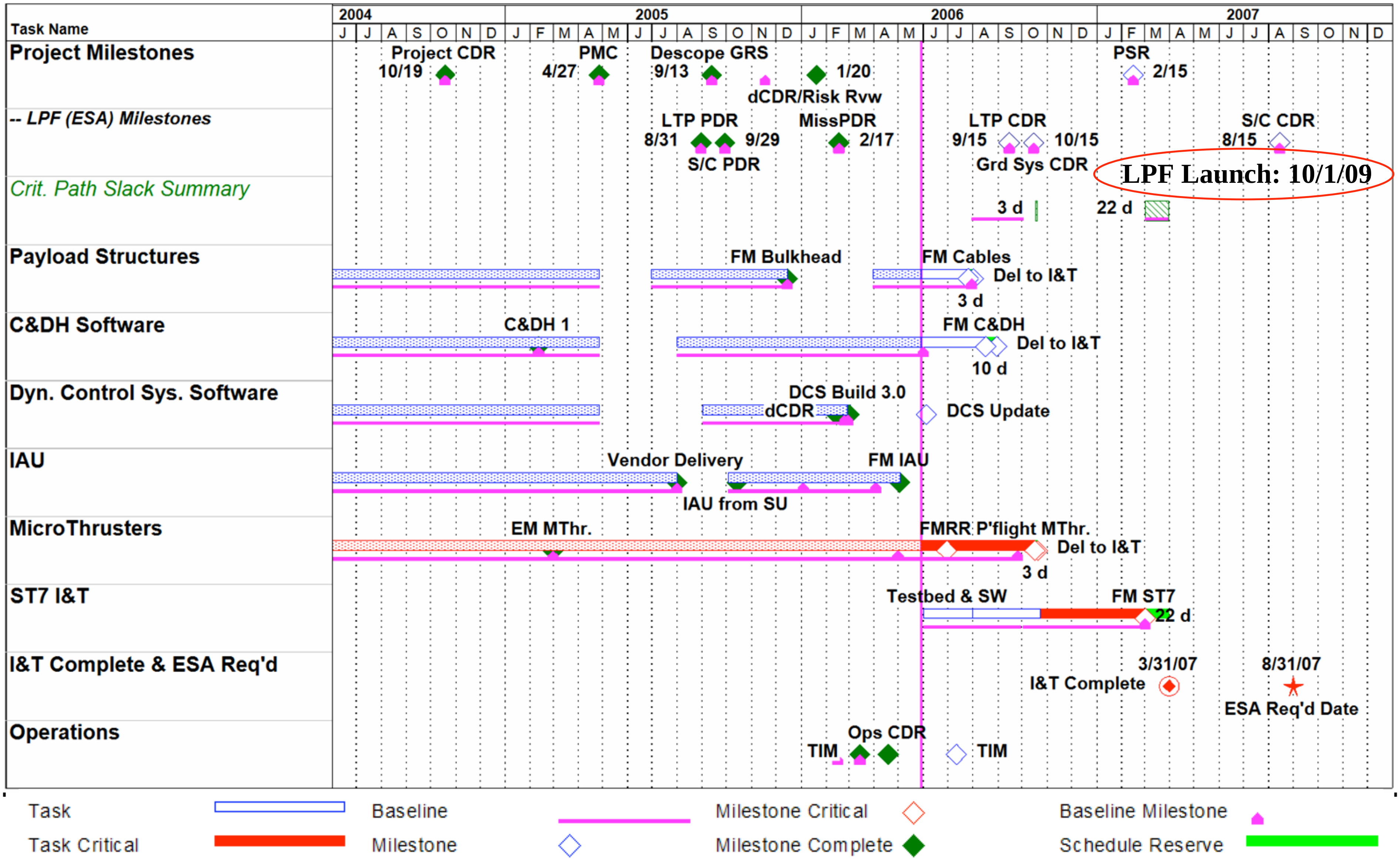
- ST-7 is developing enabling Drag-Free Control technology:
  - Low noise micro-thrusters
  - Drag-Free control algorithms
- Flight Computer & Dynamic Control Software are complete
- Colloid Micro-Newton Thrusters are beginning ground-based performance testing.

I&T Flow

DRS Integration and Test Milestones Flowchart



Top Level Schedule



Technical Margins

Resource	Current Best Estimate	Allocation	Margin (Design Principles)
Mass	37.5 kg P	43 kg	13% (5% @ ARR)
Power	68.8 W P	78 W	12% (10% @ ARR)
IAU RAM Memory	69 MByte M	128 MByte	46% (20% @ Launch)
EEProm Memory	4 MByte M	16 MByte	75% (20% @ Launch)
Cycle Time	11 ms P	100 ms	89% (20% @ Launch)
Thruster ROM	18.6 kByte M	32 kByte	42% (20% @ Launch)*
Thruster RAM	518 Byte M	32.25 kByte	98% (20% @ Launch)*
Thruster Cycle Time	90 ms M	100 ms	10% (20% @ Launch)*
Propellent (30 μN, ea)[1] **Design (90 days)** **Baseline + Comm** **Minimum + Comm**	99 days at 30 μN E 159 g 123 g 35 g	90 days 175 g	10% margin in days 9% 30% 80%
Propellent (20 μN, ea)[2] **Design (90 days)** **Baseline + Comm** **Minimum + Comm**	99 days at 20 μN E 91 g 71 g 20 g	90 days 100 g	10% margin in days 9% 29% 80%

* Thruster software is fixed program. The thruster algorithm can be changed by using a C&DH capability to override thruster programming using thruster diagnostic mode. This code resides in the IAU and has ample margin.

1,2: Estimate is usable propellent only. Additional, unusable propellent is (1) 6.5 grams and (2) 5.75 grams. Maximum usable bellows fill is 615 g/cluster- 11.7 additional days at design thrust.

M: Measured
P: Partially Measured
E: Estimate